Implications of alternative methods of computing blood pressure means
Laura M. Glynn, Nicholas Christenfeld and William Gerin*

Background Blood pressure measures are traditionally averaged to compute a level across a period. There are, however, two ways of calculating such means: by assigning equal weights to each time interval or to each heartbeat. The former method is used commonly with intermittent measures, the latter with continuous measurements, though either can be calculated with either monitoring technique. For periods during which there is substantial variability in the cardiovascular levels, and in which the pulse is correlated with the blood pressure, the two techniques will produce different results.

Methods We illustrated the difference between the two techniques by calculating mean blood pressure levels during two episodes, with the heart rate and blood pressure monitored continuously using the Finapres 2300 blood pressure monitor.

Results During the first episode, there was dramatic variability in heart rate and blood pressure. The pulse-based calculations, which give greater weight to the periods during which the pulse is elevated, gave means for the systolic and diastolic blood pressures substantially higher than those obtained using time-based methods. During the second episode, both the heart rate and the blood pressure were stable, and we observed no difference between the results from the two methods of calculating the means.

Conclusions Because there are theoretical justifications for both methods of computation, and they can produce different results, it is important that researchers attend to the difference, and describe the technique used when presenting results.

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Introduction

Although methods of blood pressure measurement may be characterized in a variety of ways, one important differentiation concerns the use of continuous versus intermittent sampling methods. Intermittent methods, ranging from the traditional sphygmomanometer to the ambulatory blood pressure monitor, predominate both for clinical and for research purposes. Continuous methods of recording, however, do hold certain advantages, and they too are used frequently for these purposes. Intra-arterial recording is regarded as the optimal means of blood pressure measurement [1], and has been the method against which other methods have been validated. In the laboratory, noninvasive blood pressure recordings are frequently obtained using a device such as the Ohmeda Finapres (Ohmeda, Louisville, Colorado, USA), which uses the Penaz method to detect variations in finger arterial pressure [2].

When mean blood pressures are computed, there is, at least implicitly, a choice of computing those means over time or computing them over heart beats. With intermittent monitoring, the usual procedure is to compute the means per unit time. That is, a series of pressures will be obtained at evenly spaced intervals for some predefined period, such as blood pressures of subjects 'at work' or 'awake', and all of these pressures will be averaged. On the other hand, with continuous monitoring, the typical procedure is to compute the means per heart beat. A pressure will be obtained every time the heart beats, and all of these will be averaged. The time-based technique represents the best estimate of what the blood pressure would be if one were to pick a random time from the whole interval and measure the blood pressure. The pulse-based technique provides the best estimate of what the blood pressure would be if one were to pick a random heart beat from the whole interval and measure the pressure. It is possible to use either technique of mean computation with data from either continuous or intermittent monitoring, and so the technique of blood pressure monitoring does not commit the researcher to a particular method of computing means. Nonetheless, the usual procedure is for time-sampled data to be averaged in the time-based way, and continuous data to be averaged in the pulse-based way.

There are situations in which these two techniques can produce quite different results. This will occur when there is a substantial amount of variability in the heart rate, and
when the heart rate is correlated with the variability in the blood pressure. That is, if the heart rate changes dramatically over the interval, and the blood pressure tends to be higher when the pulse is elevated, then the two ways of calculating the means can produce quite different outcomes. This can be illustrated with a hypothetical example. Let us suppose that during two minutes of intermittent monitoring the heart rate remains steady at 60 beats/min for the first minute, and then increases to 120 beats/min for the next minute. Let us further suppose that the blood pressure also starts low during the first minute, and then increases to a higher level during the second minute. If the blood pressure is measured every 30 s, then we will obtain two lower blood pressure readings, and two higher readings, and the mean blood pressure over these four measurements will be right in the middle. This will be a time-based mean. (Note that the sampling intervals need not be spaced evenly to produce a time-based mean, when the readings are averaged. Any sampling technique, either random or evenly spaced, will produce the same result, so long as the sampling interval is independent of the heart rate and blood pressure levels.) On the other hand, if we were to monitor the blood pressure continuously, obtaining a reading at every heart beat, we would have 60 lower readings and 120 higher readings. The mean of these 180 measurements (a pulse-based mean) would be higher than the mean computed the time-based way owing to the greater number of higher pressures included in the sample.

Neither of these methods, time-based and pulse-based, is necessarily the 'correct' way to compute means. The usefulness of one method relative to that of the other can depend on the specific question under investigation. For example, one might care about the strain on the cardiovascular system in terms of the amount of time that the blood pressure is elevated. That is, the impact on the system might depend on how many seconds the blood pressure remains high. In such a case, time-based means will provide more useful estimates. On the other hand, the impact might be produced not as a function of time, but of heart beats. The strain on the system might depend not on the elapsed time, but rather on the number of high-pressure pulses that travel through the system, and thus the more useful mean would be that obtained using the pulse-based technique.

Fortunately, it is possible to apply both methods of computing means to data collected either intermittently or continuously. With continuous monitoring, for which there is a blood pressure reading for every heart beat, averaging all of the blood pressure measurements within the period under study will produce a pulse-based mean. In order to calculate a time-based mean from continuous data, one can weight each blood pressure measurement by its associated interbeat interval (IBI).

Thus, the more numerous blood pressures occurring during periods when the heart rate is higher will receive less weight than the less frequent measurements that occur when the heart rate is lower. (Another method of performing this transformation is to calculate a mean per unit time, such as a mean for every second, and then average these means. Such an average would not give any more weight to periods during which the pulse was higher than it would to periods during which the pulse was lower. The actual interval over which the pressures are averaged is not important, so long as it is short enough that there is relatively little pulse variability within the interval.)

It is also possible to transform intermittently sampled blood pressure scores into pulse-based means. This can be done by weighting each blood pressure measurement included in the computation of the average by the heart rate at the time the measurement was taken. This way, pressures taken when the pulse was higher will be given more weight, whereas those taken when the pulse was lower will count less toward the mean. This reflects the fact that there are more systoles and diastoles in periods during which the heart rate is elevated.

Although we have discussed the impact of the two mean-computation techniques in terms of the blood pressure, the same principles apply to the calculation of the heart rate itself. In fact, there are two reasons that the differences can be even more dramatic for this measure than they are for the blood pressure. First, the variability in heart rate tends to be greater than that in blood pressure. Although a threefold increase in heart rate is quite possible, such an increase in blood pressure is extremely unlikely. Furthermore, as discussed above, the differences between the blood pressure means calculated using the two different methods depend in part on a positive correlation between the blood pressure and the heart rate. For the computation of mean heart rates, because the sampling rate is the same as the heart rate, this is not a limitation. The mean heart rate, just like the mean blood pressure, can be interpreted meaningfully with either calculation. The time-based calculation represents the heart rate at a randomly selected time, whereas the pulse-based calculation represents the heart rate for a randomly selected heart beat. Again, the impact on the heart might depend either on the length of time the pulse is elevated or on the number of beats for which it is elevated, so either calculation might be clinically useful. However, in the case of the heart rate, use of time-based means makes greater intuitive sense. For example, the time-based heart rate, in beats per minute, will reflect the number of times the heart will beat during 1 min. It is for this reason that continuously monitored heart rates, which are more commonly used than continuously monitored blood pressures, are often converted from beats/min to IBI. Averaging these produces a time-based, rather than a pulse-based, mean.
We will illustrate these points with two examples of actual physiologic data. In the first, we will present a case in which there was a dramatic variability in the heart rate during the course of the session, and in the second we will present a case in which the heart rate varied little during the session.

**Methods and results**

**Case 1**

We recorded a 2 min laboratory session during which the subject went from a relaxed baseline state to vigorous physical exercise in order to produce a large change in the cardiovascular measures. Blood pressure and heart rate data were collected using an Ohmeda Finapres 2300 blood pressure monitor. This device records beat-to-beat pressures in a noninvasive manner, using the Penaz method [2], and allows systolic and diastolic blood pressures, as well as the heart rate, to be read and stored. The method of operation of the Finapres monitor has been described in detail by several authors [2,3].

After the subject had been instrumented, the subject remained still and relaxed for 80 s, and then exercised vigorously for 40 s. The resulting blood pressure and heart rate measurements are shown in Figure 1. The heart rate went from a resting level of approximately 60 beats/min to an exercise-induced level of about 150 beats/min. It is clear that this session satisfied the first requirement for producing differences between the two computation techniques in that there was a marked variability of the heart rate within the period. The systolic and diastolic blood pressures also rose significantly during this period, from resting levels of approximately 120/60 mmHg (systolic blood pressure/diastolic blood pressure) to roughly 190/110 mmHg. The correlations between the heart rate and blood pressure measurements were quite strong ($r = 0.853$ for the systolic blood pressure and $r = 0.942$ for the diastolic blood pressure). Thus, these data also satisfied the second requirement for obtaining differences between the two computation techniques.

The average of all the measurements, one per heart rate, produced mean blood pressures of 133.1/71.6 mmHg. The mean heart rate, again using the pulse-based technique, was 102.7 beats/min. These represent the cardiovascular levels for the average heart beat during the 2 min session. The data were transformed in order to calculate time-based means for the same session. This produced blood pressure means of 125.8/67.5 mmHg. These numbers were obtained by weighting each pressure reading by its associated IBI. The heart rate, calculated in the normal time-based manner, was 88.1 beats/min. In keeping with the intuitive meaning of this way of computing the heart rate, the subject's heart actually did beat 177 times during the 2 min, for an average of 88.5 beats/min.

![Fig 1](image.png)

**Case 1:** 2 min of blood pressure and heart rate data taken during 80 s of rest and 40 s of vigorous exercise. BPM, beats/min; $\Delta$, systolic blood pressure; $\Delta$, diastolic blood pressure; $\bullet$, heart rate.

It is clear from this example that the two techniques can produce quite different results. The pulse-based technique resulted in a systolic mean 7 mmHg higher and a diastolic mean 4 mmHg higher than the means obtained from the time-based technique. The heart rate means exhibited the greatest difference: the value for the pulse-based calculation was 14.6 beats/min higher. So long as the blood pressure and heart rate are correlated positively, the pulse-based means will be higher. The difference, however, will not always be so dramatic as that presented here, since, during a single testing session, the heart rate will rarely vary as much as it did in this case. To illustrate a case in which the two techniques should not provide very different estimates, we conducted a second session, during which the subject did not exercise, but simply remained calmly seated.

**Case 2**

The same subject as that in our first example was instrumented with the Finapres device again, and monitored for 2 min. This session was exactly the same as the first, except that the subject remained still and relaxed throughout the 2 min. The blood pressure and heart rate data are shown in Figure 2. The heart rate varied only slightly during the session, being mostly in the range 60-70 beats/min. The blood pressures were also fairly stable, hovering around 110/70 mmHg. Unlike during the first session, the blood pressure and heart rate were not correlated strongly ($r = 0.095$ for the systolic blood pressure and $r = 0.365$ for the diastolic blood pressure). It is worth noting, though it is not central to the argument of this paper, that, although there was little variability in blood pressure, the minor fluctuations that did occur in systolic and diastolic blood pressures, albeit mostly
unrelated to the heart rate, were related extremely closely to each other ($r = 0.897$).

Because of the reduced variability, and the much smaller correlations between heart rate and blood pressure measures, the two computation techniques should make little difference in this case. The pulse-based blood pressure means, again simply the average of the score obtained at each heart beat, were 111.1/66.6 mmHg. The pulse-based heart rate mean was 67.3 beats/min. Converting to time-based means produced blood pressure means of 111.2/66.6 mmHg, identical to the pulse-based technique. The heart rate mean, computed with the time-based technique, was 67.5 beats/min. There were, as there should be, 135 actual pulses recorded during the 2 min session.

**Discussion**

Whereas the first case demonstrates that the two techniques can produce quite disparate results, the second case illustrates clearly that this will not always be so. If one is interested in the means for a period during which there is little variability, then it will not matter from a practical standpoint whether the calculation is time-based or pulse-based. Furthermore, in laboratory stress testing in which there is more dramatic overall variability in the heart rate and blood pressure, the experimenter might want to try to isolate the resting and stress phases, to reduce the variability within phases. That is, a separate mean is generally computed for the baseline and stress phases. However, even in such cases, the method of computation can make a difference. For example, there is generally a lag between the start of the stressor and the full cardiovascular response. If the stressor phase starts

when the stressor is imposed, the subject’s heart rate and blood pressure will vary quite significantly during this phase. One could reduce this by discarding the initial response to the stressor, but since this will vary among subjects, and among stressors, it might not be a useful solution to the problem. Furthermore, eliminating the initial response to the stressor could result in discarding valuable information about the subject.

The two techniques may also make an important difference during ambulatory monitoring. In these sorts of studies, there may not be such distinct phases as those which occur in the laboratory (e.g. baseline and stress), and subjects’ blood pressures may well exhibit wide excursions during the monitoring, especially for around-the-clock monitoring that includes sleeping and waking periods. During sleep the blood pressure and pulse of most subjects will both be low, and there will be large differences between this state and normal daytime levels. In such cases, deciding between time-based and pulse-based means will be of some potential significance. The difference could also be of some importance if there are individual differences in heart rate variability or in the extent to which the heart rate and blood pressure covary. In such cases, the difference between these two techniques could result in a different rank ordering of subjects’ mean blood pressure levels. The difference could also be significant if some researchers report time-based means and others report pulse-based means, because the difference would reduce the comparability of their results.

In conclusion, it is important for researchers who collect and analyze blood pressure data, using either intermittent or continuous methods of monitoring, to choose between the time-based and pulse-based methods. The choice should be based on the research question and the nature of the data. It would also be useful for researchers to provide details concerning the methods of computation used.

**References**

